20 November 1964 RSIC-328

WATER TUNNEL DESIGN AND RELATED INSTRUMENTATION CONSIDERATIONS AND A SELECTED BIBLIOGRAPHY ON INCOMPRESSIBLE INTERNAL FLUID FLOW

by

J. L. Harp, V. O. Hoehne, J. M. Allen, and G. R. Whitacre
Battelle Memorial Institute
Columbus, Ohio

Contract No. DA-01-021-AMC-203(Z)

Research Branch
Redstone Scientific Information Center
Directorate of Research and Development
U. S. Army Missile Command
Redstone Arsenal, Alabama

ABSTRACT

This report presents the results of a state-of-the-art survey on flow-tunnel design and related instrumentation for tunnels using water or liquid nitrogen as the working fluid. The scope of the survey is purposely narrowed by considerations of the proposed tunnel to be designed and built at NASA's George C. Marshall Space Flight Center (MSFC). Initial application of the proposed tunnel will include internal-fluid-flow studies of cryogenic fuel-system components or combinations thereof.

Major considerations applicable to the principal components of the proposed tunnel are presented. Some specific recommendations are also presented for consideration by those who will undertake the actual design and operation of the proposed tunnel.

Literature Cited are listed at the end of the report for further detailed study. Many of these references are, in themselves, design studies for liquid-flow tunnels or flow-tunnel sections.

Also included is a selected bibliography on internal fluid flow, with a brief description of each. The categories included are pressure drop; flow patterns including curved flows, mixing, and flow measurement; visualization including flow modeling, cavitation, and transients; flow of cryogenic fluids; and two-phase flow.

FOREWORD

The purpose of this program is to provide a state-of-the-art literature survey on water-tunnel design and related instrumentation and a selected bibliography on internal fluid flow. Special considerations for the tunnel being contemplated and taken into account in this survey include:

1. The tunnel is to have flow conditions of 4500 gallons per minute and 70 feet of H_2O pressure head across the pump to provide a velocity of 50 feet per second through a 6-inch-diameter test section.

2. The tunnel is to be used to study internal-flow phenomena.

3. The fluids of interest include water and liquid nitrogen.

Information for this report was obtained from an open-literature search at the Battelle library; the card-index file in the RSIC library at the Redstone Arsenal; the Technical Abstracts Bulletins published by the Defense Documentation Center; and visits to the Ordnance Research Laboratory at the Pennsylvania State University and the NASA Lewis Research Center.

It is difficult to specify the exact sources covered in the bibliography on internal fluid flow, since the compilation includes many items from personal files. A complete search of American Society of Mechanical Engineers (ASME) literature and the Proceedings of the Cryogenic Engineering Conferences for the past 5 years was made. In addition, other references came from the personal scanning over the last 5 to 10 years, by people working in this area, of the Technical Abstracts Bulletins, Atomic Energy Commission (AEC) literature, and many pertinent journals.

References on internal fluid flow are listed alphabetically within each category by major personal author for books and journal articles, and by corporate source for document and report-type literature. A separate personal-author index (indicating reference numbers) is also included for all references in the bibliography. Although some references apply to more than one category, they have been summarized only in the most pertinent category. Cross references to other sections are listed by reference number at the end of each section.

Appreciation is expressed to Dr. Barnes McCormick and Dr. J. William Holl of Pennsylvania State University, and Mr. Robert S. Ruggeri and Mr. Donald M. Sandercock of NASA's Lewis Research Center for their assistance.

TABLE OF CONTENTS

Section I. INTRODUCTION

Water tunnels for hydraulic studies date back over 50 years. Even though these early tunnels[1] were used primarily to investigate external flow, tunnel-design technology has continued during this period and also has been improved through tunnel-design studies. Because of the extensive and detailed design studies that have been conducted on tunnels and tunnel components, this report presents the water-tunnel information only briefly, and references the sources for more detailed study. Available information is also presented on cryogenic tunnels and on tunnel instrumentation. The specific tunnel under consideration is required to provide a uniform maximum velocity of 50 feet per second through a 6-inch-diameter test section. Such a tunnel would include a replaceable test section, diffuser, pump, and settling and contraction section, comprising a closed-loop system. Special attention was given to a requirement that the proposed tunnel could utilize liquid nitrogen as an alternative working fluid.

In the general design of the fixed-flow circuit, special attention must be directed toward cavitation inception and prevention, temperature control, and flow geometry as it affects the velocity profile at the test-section entrance. The design of the convergent section is critical in that at least partial corrections in undesirable upstream-flow profiles can be accomplished with proper design. The use of vaned elbows and a conservative diffusion angle is considered important. The use of a centrifugal pump is indicated, and suitable pumps are available from conventional sources which incorporate seals and bearings suitable for cryogenic use. Although the control of working-fluid temperature and heat pickup are important when water is used as the working fluid, this aspect becomes paramount when cryogenic fluids are used. The use of a cryogenic bath appears warranted for the proposed tunnel. Adequate information is available to support the choise of basic construction materials, coatings, and insulation for a cryogenic tunnel.

Instrumentation and techniques are available for measuring pressures, temperatures, etc., as may be required for operation with either water or liquid nitrogen as the working fluid.

These observations have been incorporated into general recommendations to guide the design of the proposed tunnel. If these considerations are adequately handled, the proposed insertion of missile components within the test section appears to be realistic.

The selected bibliography is a compilation of references on internal fluid flow. Rather than being limited strictly to a library literature search, it includes appropriate items taken from personal files and references of a number of people working in this area. In addition to a brief description of each reference, in many cases some evaluation of its usefulness has been given.

In general, only incompressible, turbulent, internal flow has been stressed. However, references are included from outside this area if any parts of the work described have application in this area. The references have been divided into seven categories as follows:

1. Pressure Drop

2. Flow Patterns Including Curved Flows

3. Mixing

4. Flow Measurement and Visualization Including Flow Modeling

5. Cavitation and Transients

6. Flow of Cryogenic Fluids

7. Two-Phase Flow.

Because the main interest in two-phase flow phenomena would be in the area of cavitation, this was made a separate category. The general two-phase flow category is quite brief, listing mainly other survey-type reports that would provide access to the vast amount of literature existing in this area.

Section II. FLOW-TUNNEL CONSIDERATIONS

A large variety of flow tunnels have been constructed for various types of hydraulic investigations.[1] Because this state-of-the-art study is concerned with the collection of information which will assist in the design of a tunnel for investigating internal flow, the study is limited to the available literature on the closed-jet type of tunnel and tunnel components. Based on considerations of the flow rate of the planned tunnel, economy, desired visual capability within the test-section region, and nonautomated instrumentation for the tunnel (at least initially), the study is further limited to information on the design of closed-circuit types of tunnels.

1. Flow Circuit

A number of studies have been performed that have resulted in relatively complete guidelines for the design of closed-circuit water tunnels. Notable among these are the studies done at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota[2] and at the ordnance Research Laboratory of Pennsylvania State University.[3,4,5,6,7] Subsequently, the theory and procedures included in these reports have been used to design tunnel systems.[1,8] Additional references[9,10,11,12,13,14] were later identified as pertinent to water-tunnel design, but most of these were not available to this study. Another source of information on existing water-tunnel facilities is the Proceedings of the ASME Symposium on Cavitation Research and Techniques.[15] Papers presented at this symposium describe tunnel facilities and techniques used for studying cavitation in fluid systems. Because the prevention of cavitation is essential to the economic operation of most fluid systems, much of the information presented during the symposium is pertinent to the design of water-tunnel facilities.

Most of the work reported in the above cited literature was done during the early 1950's. Because of this, advances in materials and material-protection techniques for flow tunnels have outdated some of the design information. However, because structural-design information is a minimum in most of these reports and because fundamental hydrodynamic theories have changed little over the years, the reported information is still very pertinent to water-tunnel design.

Figure 1 presents one possible flow-circuit configuration for a water or liquid-nitrogen tunnel, incorporating good design features based only on a preliminary study of the above references and from discussions with NASA-Lewis Research Center and Pennsylvania State University personnel. These features include:

1. An area-contraction ratio between 9 to 16, with values in the lower portion of this range preferred.

2. A heat exchanger (if needed) located at the minimum fluid-velocity portion of the circuit to reduce flow losses.

3. A maximum of 5 degrees total-diffusion angle throughout the circuit to enhance uniform-flow conditions.

4. Corner-turning vanes to reduce energy losses and minimize disturbances to the tunnel test-section flow.

5. A minimum amount of the flow circuit located outside the liquid-nitrogen cooling bath. The only part of the circuit not in the bath is that part which requires changing to accommodate various missile fuel-system configurations. This part requires the installation of a suitable insulation material.

6. Supports that allow for tunnel contraction and expansion due to large temperature changes on cooldown and warmup when using liquid nitrogen as the test fluid.

The flow circuit in Figure 1 is similar to several existing tunnel configurations.[1,2] This type of recirculating tunnel consists of the high-velocity test section, a diffuser, a variable-speed pump, a settling region and contraction section, a heat exchanger, and elbow sections with turning vanes. A brief discussion follows pertaining to each of the above, with references identified for more detailed study.

a. <u>Test Section</u>

Because the primary purpose for the proposed tunnel is to test circuit components of missile cryogenic-fuel systems, the test section of the proposed tunnel is a replaceable section which can vary throughout the range of possible combined configurations of fuel-system components. The chief requirement placed on the tunnel, therefore, is that it must supply a steady, radially-uniform fluid stream to the entrance of the test section. Ross and McGinley[4] have developed

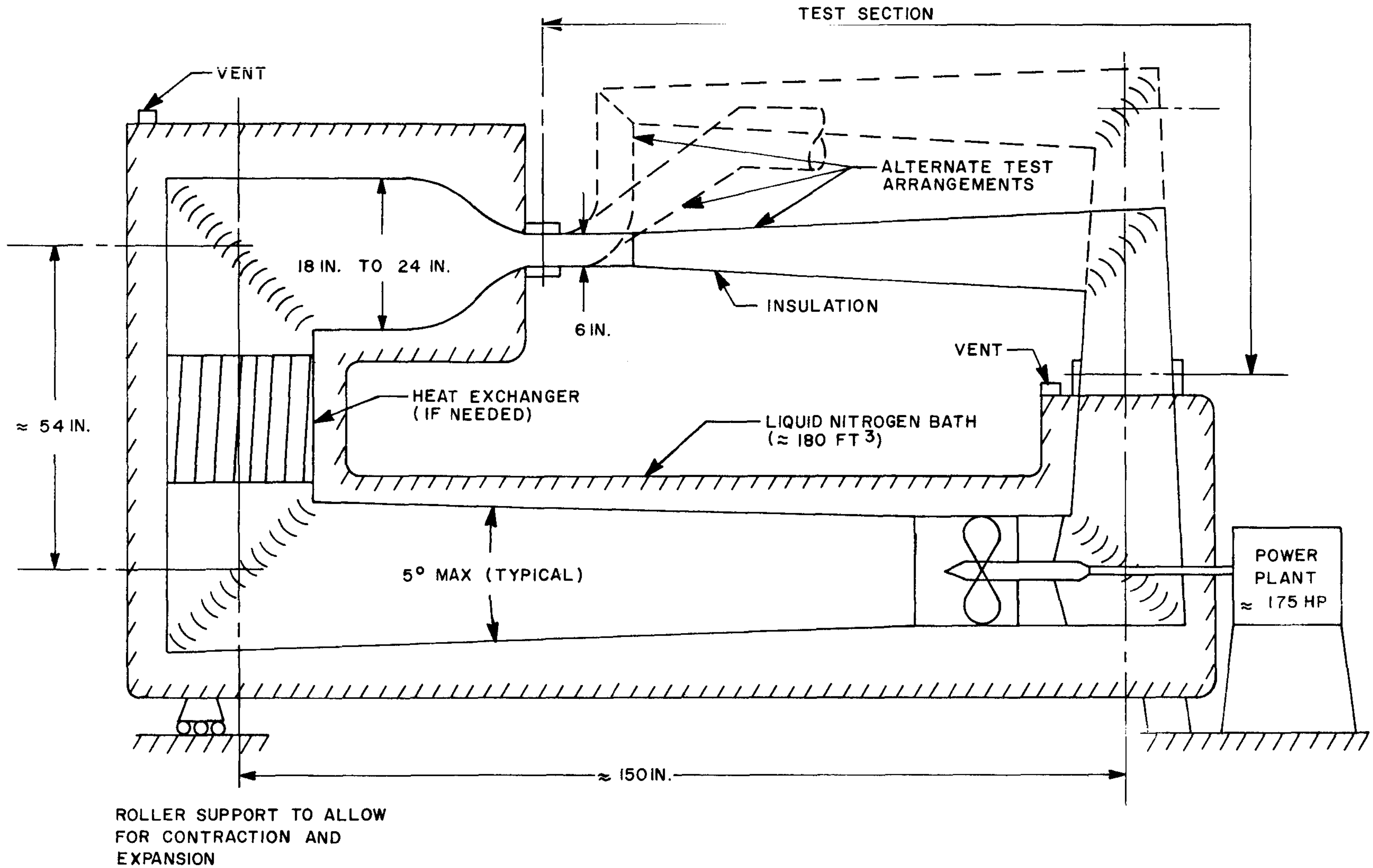

Figure 1. Possible Flow-Circuit Configuration for Water or Liquid-Nitrogen Tunnel

equations for the growth of the boundary layer in the entrance region as well as pressure and energy-head losses in working sections. Theory is compared with experimental data in their studies of closed-jet working sections.

Olson[14] has conducted studies on closed-jet working sections with divergent walls where it is desirable to eliminate the static-pressure gradient or to permit tests to be made at a lower cavitation index. Ripken[2] has also conducted detailed studies that are appropriate to the design of the test section of the proposed tunnel.

To achieve realistic results of tests of the fuel-system components, the components should have inlet-velocity profiles that are representative of the profiles that exist in the actual system of which the component is a part. The working-fluid velocity profile can change from a very uniform shape with a minimum thickness of boundary layer to a shape in which the majority of the flow cross section is in the boundary layer. These changes are a function of the turbulence level in the working fluid and the length of fluid run in a constant cross section cylindrical section. Therefore, control of the shape of the velocity profile for realism can best be achieved by varying the length of the cylindrical portion of the test section just upstream of the test component (within reason, of course) and by introducing controlled turbulence into the working fluid.

b. Contraction Section

The achievement of radial uniformity of fluid velocity at the entrance to the test section is a function of the configuration of the contraction section and the velocity distribution of the flow entering the contraction section.

Ripken points out that a properly-shaped contraction will provide a strong corrective action to velocity variations in a fluid stream, providing that a substantially-uniform pressure distribution can be achieved in the flow sections both preceding and following the contraction. Uniform pressure distributions are a result of maintaining parallel (noneddying) flow in all sections of the flow circuit. Upstream parallel flow is dependent upon the quality of the recirculating system, i.e., in the proper design of the turning vanes, in the provision of flow straighteners as necessary, etc., to provide for the prevention of separation and the resultant eddying-flow patterns. The selection of a proper contraction ratio can provide a velocity variation across the entrance to the test stream of less than 1 percent. Based on reasonable construction costs and the velocity variation figure of less

than 1 percent, the contraction ratio usually required is from 9 to 15. The radius of curvature of the contraction boundary must never be great enough to cause the fluid to separate, owing to the centrifugal force of the fluid under curved flow being greater than the pressure forces acting on the fluid. Ripken details a number of different approaches taken to establish the shape of contraction curves that have been employed in American and European water tunnels. After presenting these analyses, he describes experimental studies that include the measurement of velocity distributions, separation-zone pressure distributions, and energy losses.

c. Diffuser Section and Vaned Elbows

The purpose of the diffuser section is to reduce the high-velocity test stream from the working section to a lower value throughout the remainder of the tunnel. This reduction of velocity serves a number of related purposes including a reduction in pumping-power costs owing to reduced frictional-energy losses (power varies as velocity cubed); the minimization of the destruction of the initial uniformity of the fluid motion while returning the test fluid through 360 degrees to the entrance of the working section; and the reduction in temperature rise of the working fluid or the reduction in heat-exchanger requirements with reduced frictional-energy losses. Ross and Robertson[3, 11, 12, 16] have conducted extensive flow studies in water-tunnel diffuser sections. These studies have included the development of an analytical method termed "Superposition Analysis" which yields good theoretical predictions of velocity profiles in diffusers. This method gave results that compared quite favorably with experimental data obtained in a 7.5-degree diffuser. Steele,[7] in summarizing the results of Ross and Robertson's design studies conducted for the 48-inch water tunnel at the Ordnance Research Laboratory of Pennsylvania State University, stated that "the optimum diffuser angle was a function of the total diffuser angle, the effective working section length, and effective working section diameter."

Ripken[2] also describes numerous considerations for the design of diffusers for flow tunnels. He concludes that 5- to 7-degree diffusers may be used, although the 5-degree diffuser is preferable, owing to the decreased likelihood of separation with subsequent cavitation occurring.

In the flow circuit of Figure 1, diffusion continues through the first two vaned elbows. This design approach is taken to provide for a flow tunnel of decreased length to enhance the use of a cryogenic

bath for insulation when using liquid nitrogen as the test fluid. It is pertinent to point out that a careful study of the vaned elbows with such a design is needed. Ripken describes extensive design studies on vaned elbows. Similar studies appear desirable for the proposed tunnel.

d. Pumps

The information on pumps and their application in facilities comparable to the proposed water tunnel is extensive.[17, 18, 19] The fundamentals of this general subject will not be reviewed here. It can be stated, however, that suitable pumps are available for application such as in the proposed water tunnel.

Based on the flow-tunnel requirement of a flow rate up to 4500 gallons per minute, a maximum head of 75- to 100-feet H_2O across the pump, and a maximum shaft speed of 1750 revolutions per minute, the specific speed of the pump can be determined from the relation:

$$N_S = \frac{N\sqrt{Q}}{H^{3/4}} \quad ,$$

where NS is the specific speed, N is the pump speed in revolutions per minute, Q is the pump discharge in gallons per minute, and H is the pump head in feet.

This relation yields a specific speed from 3700 to 4600 for a 75- to 100-foot head, which indicates that a centrifugal pump would be preferred for the proposed tunnel. Sandercock[20] at Lewis Laboratories confirmed the preference for a centribugal pump and also suggested that an inducer stage ahead of the centrifugal pump might be desirable to decrease the likelihood of cavitation with low pump-inlet pressure. Acosta[21] and Montgomery[22] have conducted inducer studies for cryogenic pumps. The inducer is an extension of the main rotor, enabling it to be run at a higher speed than the impeller on a coaxial shaft. The resultant additional head rise enables the main-pump impeller to run cavitation free.

Another pump consideration, in addition to freedom from cavitation, is that the fluid stream from the pump should be constant in flow and free of pulsations. Also, the flow should be free of rotation at all rates of discharge.

The pumping of cryogenic liquids such as liquid nitrogen introduces a number of special considerations. Jacobs, Martin, Van Wylen, Birmingham, and Hardy[23,24] have conducted experimental studies on pumping liquefied gases and have identified bearings and seals as two of the major problem areas for such pumps. Standard ball bearings fabricated from AISI 52100 steel and Type 440C stainless steel and containing suitable nonmetallic separators as substitutes for metallic separators[25] can provide satisfactory bearing service when submerged in liquid nitrogen. Carbon seals are normally used in liquid-nitrogen pumps at NASA-Lewis Research Center; pump details can be discussed with the pump supplier.

e. Heat Exchanger

Because the energy input of the pump shaft increases the enthalpy of the test fluid, it may be necessary to incorporate a heat exchanger into the proposed tunnel in order to maintain the working fluid at a constant temperature. Steele describes in rather complete detail the steps involved in determining the cooling requirements and heat-exchanger design for a water tunnel. Ripken[2] and Lehman[6] also discuss cooling requirements for water-tunnel design. Procedures identified in these references are straightforward once the tunnel dimensions, materials, and operating parameters are established. Additional requirements for a cryogenic tunnel are discussed in a later section of this report. The use of a bath or immersion system as dictated for cryogenic-fluid handling may suffice for temperature control when using water as the working fluid. In either case, the effects of the temperature-control device on the temperature profiles at the test-section entrance must be considered.

f. Materials

In most of the larger water tunnels,[1,6,7,15] economics have dictated the choice of steel as the major tunnel material with a protective coating applied to prevent corrosion. Steele[7] describes "Lithglow," a phenol-base plastic, and "Durofilm," a vinyl plastic-base paint as examples of protective coatings used in water tunnels.

Materials must obviously be selected carefully for this proposed water tunnel because of the intention of using liquid nitrogen as the working fluid in the future.

Because of expansion and contraction that would occur with liquid nitrogen, carbon steel with a protective coating is undoubtedly unsatisfactory as a tunnel material. Based on properties of the

materials, stainless steel or anodized aluminum appear to be the most promising materials for the proposed tunnel. Campbell[26] and Kaufman[27] have published data that support this statement.

Ruggeri and Gelder[28] have set up a small tunnel at NASA-Lewis Research Center that will handle cryogenic as well as most ordinary liquids. This flow tunnel is fabricated from 6061 T-6 aluminum and has a heavy anodized treatment for surface protection. Double Lucite panels having a 2-inch thickness are used for the windows. A bath surrounding the tunnel is fabricated of 304 stainless steel and is insulated with ½-inch-thick composition corkboard bonded directly to the stainless steel. These materials have proven satisfactory in this tunnel application.

2. Cryogenic Aspects of a Flow Circuit

This state-of-the-art survey on flow-tunnel technology has considered both water and liquid nitrogen as test fluids. One of the most difficult problems to solve in the design of a flow circuit for cryogenic fluids is the control of temperatures to prevent liquid vaporization.

Figure 2 shows the variation of temperature and pressure for vaporization of liquid nitrogen. The stagnation temperature-pressure operating point of the liquid nitrogen must be maintained at such a level that temperature increased due to friction from power input and pressure decreased due to circuit configuration do not cause vaporization. Figure 2 also shows that the control of temperature must be more precise than the control of pressure. Note that a 30-fold increase in pressure (from 1 to 30 atm) at 140°R increases the temperature margin to vaporization by only 83°R. This shows that heat transfer and heat additions to the working fluid about the flow circuit must be held to a minimum regardless of the planned test pressures and, therefore, the choice of insulation surrounding the tunnel is critical.

There are several ways of insulating all or parts of a cryogenic-flow loop. These include immersion in a cryogenic bath, insulation by vacuum, and insulation by a low-conductivity insulating material. The preferred method, according to the personnel at NASA-Lewis Research Center, is immersion of the tunnel in a cryogenic-liquid bath. If this method is used, the total size of the flow circuit should obviously be kept to a minimum so that the quantity of fluid required for the bath does not become excessive. Also, by holding the flow-circuit size to a minimum, the heat input due to fluid friction is held to a minimum as the circuit boundaries are held to a minimum.

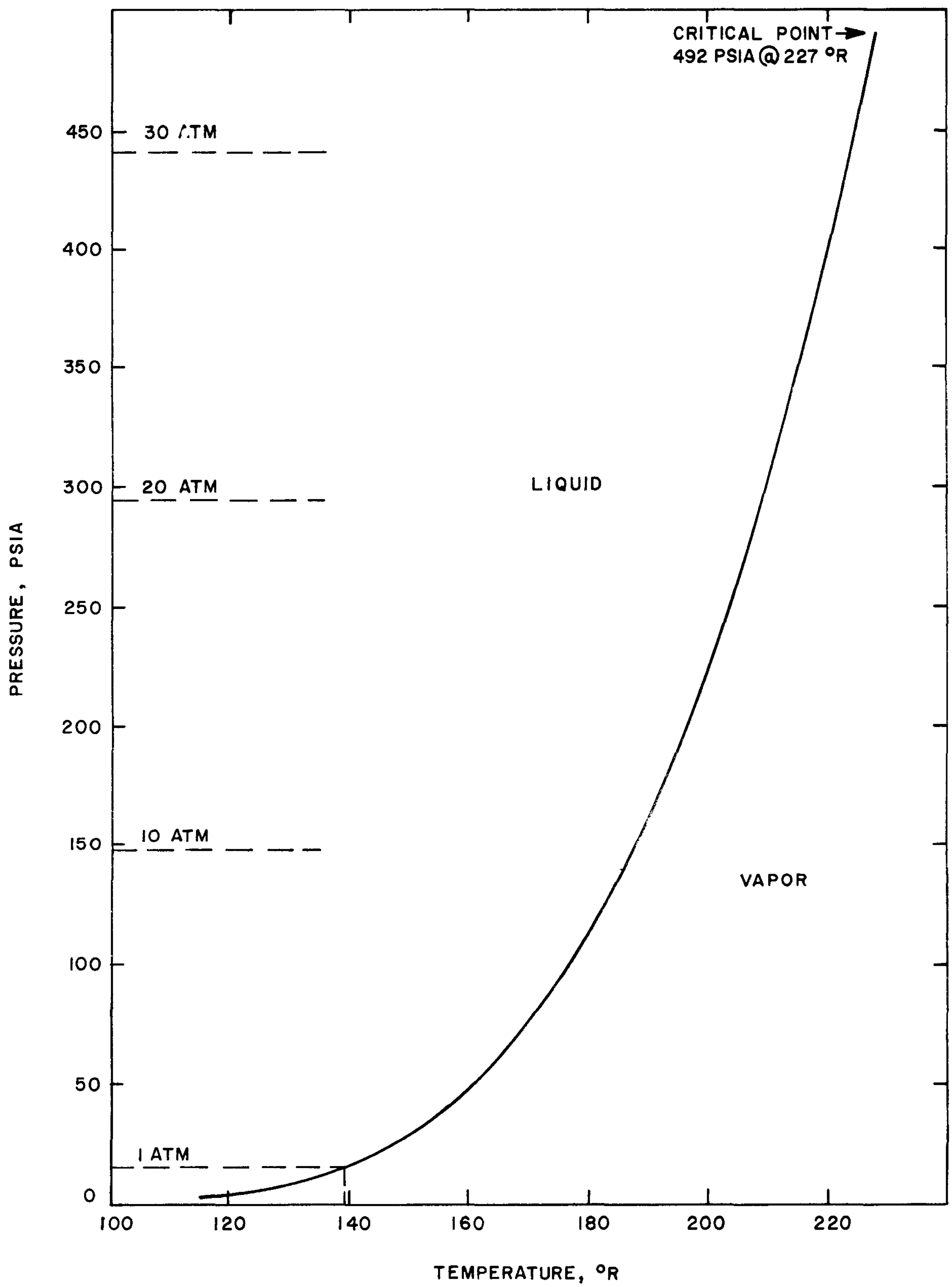

Figure 2. Temperature and Pressure for Vaporization of Nitrogen

Figure 1 shows a flow-circuit design that makes use of a cryogenic bath around all of the flow circuit except the working section. This arrangement has the advantage of a cryogenic bath, yet the convenience of ready access to the working section. This is particularly desirable if flow visualization during testing is to be utilized. Special insulations of either fibers, foams, or powders can be used on the working section. Moeller, Loser, Snyder, and Hopkins[29] have compiled thermophysical-property data for such insulating materials.

Section III. INSTRUMENTATION

Instrumentation for a liquid-tunnel system may be considered to include two specific areas; direct instrumentation for the measurement and study of phenomena in the tunnel test section, and instrumentation or controls associated with the tunnel operation.

The types of instrumentation may vary from one test-configuration installation to another, depending upon the specific nature of the planned tests. Most tunnels utilize static-pressure taps across the contraction section that are connected to appropriate manometers or other pressure read-out methods and calibrated to measured test-section velocities to facilitate monitoring velocities during tests. Pressures in the working section are measurable by conventional pressure orifices connected to pressure transducers located outside the tunnel. Ruggeri and Gelder[30] describe in considerable detail the instrumentation in the NASA-Lewis Research Center cryogenic tunnel. Copper-constantan thermocouples are used to measure inner and outer-wall temperatures as well as temperatures in the cavitated region. Absolute values of tunnel-liquid temperature are measured upstream of the contraction nozzle to within $\pm$ 0.05°F by means of a calibrated platinum-resistance thermometer. Photographic equipment is utilized to photograph cavitation phenomena through the Lucite test-section windows. Treaster[31] describes in detail the calibration of the NASA Ultra-High-Speed Cavitation Tunnel at Pennsylvania State University, which is the water-tunnel counterpart to the NASA-Lewis Research Center Cryogenic Tunnel. Information is given in that report of procedures followed for determining velocity and pressure distributions across the test-section cross section, the calibration of velocity to the pressure difference across the contaction section, and the determination of the static-pressure distribution on the test-section walls.

The Instrument Society of America has published a Transducer Compendium[32] covering all known sources of transducers complete with their characteristics. It is suggested that this reference be consulted for appropriate transducers to convert pressures to a suitable read-out for input to recording systems.

Pressure-control systems for water tunnels, along with pertinent auxiliary equipment, are described by Steele.[7] Either one form or another of the approaches described is necessary to control the working static pressure. Either the Semiautomatic Control as by Cartesian Manostat or the Fully-Automatic Control systems are preferred to a manual system.

Ruggeri and Gelder[28] discuss instrumentation and static-pressure control for the cryogenic tunnel at NASA-Lewis Research Center when using water as the working fluid. This is an excellent report because, in addition to describing the tunnel facilities and instrumentation, it presents procedures and data-reduction methods for cavitation studies.

Section IV. RECOMMENDATIONS

Although the purpose of this study was to conduct a state-of-the-art survey of water and cryogenic-tunnel design, several lasting impressions were formed during the study that are pertinent. Because of the nature of these impressions, they are best formulated as recommendations that apply to the design and development of the facility. These recommendations are:

1. Design the flow circuit and its auxiliary equipment for a cryogenic working fluid rather than for water. The most stringent requirements that will be placed on the system will be those due to the pumping, pressure regulating, and measuring functions of the tunnel while using a cryogenic working fluid. Designing the equipment necessary to perform these functions with a cryogenic fluid should result in an adequate water system, but designing for water will not necessarily yield an adequate cryogenic system.

2. Perform detailed experimental studies on critical components of the flow circuit for the purpose of optimizing these components. For example, study the spacing and angular setting of the turning vanes at a circuit corner to develop a configuration that will cause a minimum pressure loss. Perform the study by experimental and not by analytical means, because the exact analytical expressions required for the task are too cumbersome to handle.

3. Consider, during the design and development phases of the tunnel, the need for building and testing a scaled model of the system. Very often, the problems solved by this approach result in ultimate savings exceeding the costs of the model tunnel.

LITERATURE CITED

1. Pennsylvania State University, Ordnance Research Laboratory, Report No. NOrd 7958-256, "Water Tunnels for Hydraulic Investigations," Robertson, J. M., March 31, 1953.

2. University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Technical Paper No. 9, Series B., "Design Studies for a Closed-Jet Water Tunnel," Ripken, John F., August 1951.

3. Pennsylvania State University, Ordnance Research Laboratory Report No. NOrd 7958-230, "Water Tunnel Diffuser Flow Studies. Part III - Analytical Research," Ross, Donald and Robertson, J. M., March 1, 1952.

4. Pennsylvania State University, Ordnance Research Laboratory, Report No. NOrd 7958-283, "Flow in Closed-Jet Working Sections," Ross, Donald and McGinley, J. H., February 5, 1954.

5. Pennsylvania State University, Ordnance Research Laboratory, Report No. NOrd 7958-285, "Water Tunnel Transition-Section Flow Studies," Ross, Donald, June 25, 1954.

6. Pennsylvania State University, Ordnance Research Laboratory, Report No. NOrd 16597-56, "The Garfield Thomas Water Tunnel," Lehman, August F., September 30, 1959.

7. Steele, Roger L., "The Design of a Small Water Tunnel," Master's Thesis, Pennsylvania State University, June 1951.

8. Pennsylvania State University, Ordnance Research Laboratory, Report No. NOrd 7958-211, "Garfield Thomas Water-Tunnel Operations," Power, R. B., Robertson, J. M., Ross, Donald, et al., May 1, 1951.

9. Binder, R. C., "Calculation of Diffuser Efficiency for Two-Dimensional Flow," Journal of Applied Mechanics, ASME Transactions, Vol. 69, 1947, page A-213.

10. Pennsylvania State University, Ordnance Research Laboratory, Report No. NOrd 7958-97, "Water Tunnel Working-Section Flow Studies," Robertson, J. M., and Ross, Donald, June 15, 1948.

11. Pennsylvania State University, Ordnance Research Laboratory, Report No. NOrd 7958-139, "Water Tunnel Diffuser Flow Studies. Part I - Review of Literature," May 16, 1949.

12. Pennsylvania State University, Ordnance Research Laboratory, Report No. NOrd 7958-143, "Water Tunnel Diffuser Flow Studies. Part II - Experimental Research," July 8, 1949.

13. University of Minnesota, Project Report 12, BuShips Contract NObs-34208, "Model Experiments for the Design of a Sixty-Inch Water Tunnel. Part III - Test Section and Cavitation Index Studies," Holdhusen, James S., September 1948.

14. University of Minnesota, Project Report 32, BuShips Contract N600s-s-11459, "A Diverging Closed-Jet Test Section for a Water Tunnel," Olson, Reuben M., June 1952.

15. American Society of Mechanical Engineers, Symposium on Cavitation Research Facilities and Techniques, Fluids Engineering Division Conference, Philadelphia, Pennsylvania, May 18-20, 1964.

16. Ross, D., and Robertson, J. M., "A Superposition Analysis of the Turbulent-Boundary Layer in an Adverse-Pressure Gradient," Journal of Applied Mechanics, Vol. 18, pp 95-100, March 1951.

17. Hicks, T. G., Pump Selection and Application, McGraw-Hill, 1957.

18. Kristal, F. A., and Annett, F. A., Pumps, McGraw-Hill, 1953.

19. Stepanoff, A. J., Centrifugal and Axial Flow Pumps, John Wiley and Sons, 1957.

20. National Aeronautics and Space Administration, Lewis Research Center, Technical Note D-1170, "Investigation of the Performance of a 78° Flat-Plate Helical Inducer," Soltis, R. F., Anderson, D. A., and Sandercock, D. M., March 1962.

LITERATURE CITED (Continued)

21. U. S. Department of the Navy, Second Symposium on Naval Hydrodynamics - Hydrodynamics Noise - Cavity Flow, Office of Naval Research, August 25-29, 1958. (See Acosta, pp 533-557).

22. National Aeronautics and Space Administration, Lewis Research Center, Technical Note D-583, "Analytical Performance Characteristics and Outlet-Flow Conditions of Constant and Variable-Lead Helical Inducers for Cryogenic Pumps," Montgomery, John C., March 1961.

23. National Bureau of Standards, Report No. 3569, "Pumping Cryogenic Fluids," Jacobs, R. B., Martin, K. B., Van Wylen, G. J., and Birmingham, B. W.

24. National Bureau of Standards (Boulder, Colorado), "Performance of Pumps with Liquefied Gases," Martin, K. B., Jacobs, R. B., and Hardy, R. J., AD 135423.

25. Aerojet-General Corporation, state-of-the-art on "Bearing Materials for Cryogenic-Temperature Applications," AD 293596, August 15, 1962.

26. Battelle Memorial Institute, Defense Metals Information Center, DMIC Memorandum No. 94, "Review of Recent Developments in the Evaluation of Special Metal Properties," Campbell, J. E., March 28, 1961.

27. Alcoa Research Laboratories, Report No. 9-60-26, "Mechanical Properties of Plain and Welded 6061 Aluminum Alloy at Subzero Temperatures," Kaufman, J. G., July 7, 1960.

28. National Aeronautics and Space Administration, Lewis Research Center, Technical Note D-1459, "Effects of Air Content and Water Purity on Liquid Tension at Incipient Cavitation in Venturi Flow," Ruggeri, Robert S., and Gelder, Thomas F., March 1963.

29. Midwest Research Institute, Technical Documentary Report No. ASD-TDR-62-215, "Thermophysical Properties of Thermal-Insulating Materials," Moeller, C. E., Loser, J. B., Snyder, W. E., Hopkins, V., July 1962.

LITERATURE CITED (Concluded)

30. National Aeronautics and Space Administration, Lewis Research Center, Technical Note TN D-2088, "Cavitation and Effective Liquid Tension of Nitrogen in a Tunnel Venturi," Ruggeri, Robert S., and Gelder, Thomas, F., February 1964.

31. Treaster, Allen L., "Cavitation Hysteresis," Master's Thesis, Pennsylvania State University, Contract NOrd 16597, Contract NSG-85-60, AD 436602.

32. ISA Transducer Compendium, Emil J. Minner, Editor, Plenum Press, 1963.

SELECTED BIBLIOGRAPHY

PRESSURE DROP

1. ASHRAE Guide and Data Book, Applications Volume, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, New York, 1964.

   Tabulation of experimentally obtained pressure-loss data on duct fittings and intakes, Chapter 7; pipe fittings, Chapters 8, 10, and 76; pipe friction, Chapters 10 and 76; valves and fittings, Chapter 76.

2. ASHRAE Guide and Data Book, Fundamentals and Equipment Volume, Air-Duct Design, Chapter 12, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1963.

   Friction factors for various shapes of ducts are presented as well as loss coefficients for expansion, contraction, conventional and mitered elbows, take-offs, and obstacles. An extensive list of pertinent references and a bibliography complete the chapter.

3. Aktiebolaget Atomenergi Stockholm AEC Report AE-141, "Heat Transfer and Pressure Drop with Rough Surfaces. A Literature Survey," Bhattacharyya, A., 1964.

   This literaute survey deals with changes in heat-transfer coefficient and friction with varying nature and degree of roughness.

4. Columbia University, Department of Chemical Engineering, Engineering Research Labs, Report No. TID-5670, Available OTS, "Initial Experiments on Pressure Drop for Flow Through Eccentric Annuli, Part I and II," Diskind, T., Matos, C. A., and Stein, R. P., 21 pp, November 20, 1959.

   Pressure drop in concentric and eccentric annuli are experimentally determined. Friction factor is correlated as a function of Reynolds number and eccentricities for both smooth and rough annuli.

5. Daniels, C. M., and Fenton, R. E., "Determining Pressure Drop in Flexible Metal Hose," Machine Design, Vol. 32, pp 195-198, October 13, 1960.

This article presents specific data on pressure loss for flexible hose from ¼-to 4-inch diameter. Limited data on losses in flexible-hose elbows are also included. A generalized method for predicting pressure loss envolved from these data is also given.

6. E. I. du Pont de Nemours & Company, Savannah River Laboratory, AEC Report No. DP-583, "Friction Factors for Flow of Water in an Annulus with One Roughened Wall," Durant, W. S., 21 pp, June 1961.

Friction factors are obtained for water flowing in an annulus with the inner wall roughened.

7. General Electric Company, Aircraft Nuclear Propulsion Department, AEC Report No. TID-11921, "Pressure Losses Within Ducting Systems and Components for Incompressible Flow," Cliffe, R. T., Drummond, F. O., Faron, F. S., Flitner, D. P., Folchi, D. V., and Jones, D. L., January 1959.

A collection of charts and formulas for the evaluation of pressure drops in duct systems having isothermal-incompressible flow is presented.

8. General Electric Company, Hanford Atomic Products Operation, AEC Report HW-80970 (Rev. 1), "Two-Phase Pressure Drop in Piping Components," Fitzsimmons, D. E., 64 pp, March 20, 1964.

Two-phase and single-phase pressure-drop data are presented for various piping components at high pressure. A correlation was developed to relate two-phase to single-phase pressure-drop ratios of the bends to the pressure-drop ratios for straight pipe.

9. Irvine, T. F., Jr., and Eckert, E.R.G., "Comparison of Experimental Information and Analytical Prediction for Laminar-Entrance Pressure Drop in Ducts with Rectangular and Triangular Cross Sections," Journal of Applied Mechanics, Vol. 25, p 288, 1958.

   In a short note, pressure drops in the entrance region of an isosceles-triangular duct of 23-degree apex angle and a rectangular duct of 3:1 aspect ratio are compared with the results of a simplified method of prediction.

10. Ito, H., "Friction Factors for Turbulent Flow in Curved Pipes," ASME Transactions, Journal of Basic Engineering, Vol. 81, Ser. D. No. 2, pp 123-134, June 1959.

   An experimental determination using water for range of curved pipes having radius ratios from 16.4 to 648 is described. Experimental-data plots and empirical formulas are presented.

11. Ito, H., "Pressure Losses in Smooth-Pipe Bends," ASME Transactions, Journal of Basic Engineering, Vol. 82, Ser. D. No. 1, pp 131-143, March 1960.

   Experimental results of extensive studies to determine the pressure losses for turbulent-water flow in smooth-pipe bends of circular cross section are presented.

12. Lohrenz, J., and Kurata, F., "A Friction-Factor Plot for Smooth Circular Conduits, Concentric Annuli, and Parallel Plates," Industrial and Engineering Chemistry, Vol. 52 (8), pp 703-706, August 1960.

   This new approach to the annulus problem presents a friction-factor correlation which can be used without difficulty and which yields a value of the critical Reynolds number more in agreement with experiments than the standard hydraulic-radius concept. A detailed literature survey on both experimental and theoretical

studies of pressure drop through concentric annuli and parallel plates is also presented.

13. Lundgreen, T. S., Sparrow, E. M., and Starr, J. B., "Pressure Drop Due to the Entrance Region in Ducts of Arbitrary Cross Section," Journal of Basic Engineering, 620, September 1964.

A procedure is outlined for computing the entrance loss with laminar flow in a duct of arbitrary shape when the fully developed velocity distribution is known. Results are given for circular, elliptical, rectangular, isosceles - triangular, and annular ducts. Comparison with a small amount of circular and rectangular-duct data appears satisfactory.

14. Maurer, G. W., and LeTourneau, B. W., "Friction Factors for Fully Developed Turbulent Flow in Ducts with and without Heat Transfer," Journal of Basic Engineering, 627, September 1964.

The friction factor for water flowing in a 0.087- by 1-inch duct under isothermal conditions was found to agree with the conventional hydraulic equivalent-diameter modification of the circular-duct case for Reynolds numbers from 4×10^3 to 5×10^5. Data for heat inputs from 0 to 1.6×10^6 Btuh ft^2 and data in the literature on air were used to obtain a modifying parameter for isothermal-friction factor in terms of the ratio of wall-to-bulk viscosity and wall-to-bulk density. The standard deviation of this predictive relation was about 6.5 percent.

15. Pearson, H., and Heurteux, B. M. L., "Losses at Sudden Expansions and Contractions in Ducts," Aeronautical Quarterly, Vol. 14 (1), pp 63-74, February 1963.

This report shows that normally estimated losses occurring at sudden contractions and expansions are greatly increased by the low-discharge coefficient. When allowance is made for this, the losses at obstructions can be estimated reasonably accurately. It is also shown that, where obstructions are placed in series with the flow areas roughly in line, losses are much less than the total of the losses taken separately.

16. Rothfus, R. R., Archer, D. H., Klimas, I. C., and Sikchi, K. G., "Simplified Flow Calculations for Tubes and Parallel Plates," American Institute of Chemical Engineering Journal, Vol. 3 (2), pp 208-212, June 1957.

Working diagrams are presented from which turbulent-friction losses and local velocities for tubes and parallel plates can be calculated without interpolation or trial-and-error procedures. Especially useful are plots of the ratio of average velocity to maximum velocity as a function of Reynolds number including the transitional range.

17. SAE Aero-Space Applied Thermodynamics Manual, Society of Automotive Engineers, New York, Section 1, Part A, 1962.

This is a tabular and graphical presentation of incompressible fluid-pressure-loss data for a great many piping and duct fittings such as elbows, "Z" bends, "U" bends, and offset bends.

18. Smith, A. J., "The Flow and Pressure Losses in Smooth-Pipe Bends of Constant Cross Section," Journal of the Royal Aeronautical Society, Vol. 67, pp 437-447, July 1963.

Pressure losses and flow profiles are presented for smooth-pipe bends of constant cross section.

19. Walker, J. E., Whan, G. A., and Rothfus, R. R., "Fluid Friction in Noncircular Ducts," American Institute of Chemical Engineering Journal, Vol. 3 (4), pp 484-489, December 1957.

SEE ALSO REFERENCE NUMBER 21, 28, 58.

A modified hydraulic-radius concept is employed which uniquely correlates friction-factor data in the turbulent range. A theoretical expression is given for the viscous or laminar range which is in agreement with the measured friction factors.

FLOW PATTERNS INCLUDING CURVED FLOWS

20. Abbott, D. E., and Kline, S. J., "Experimental Investigation of Subsonic Turbulent Flow Over Single and Double Backward-Facing Steps," ASME Transactions, Journal of Basic Engineering, Vol. 84, Ser. D, No. 3, pp 317-325, September 1962.

Results are presented for flow patterns over backward-facing steps covering a wide range of geometric variables. Experimental work was carried out in a closed-circuit, open-surface water table.

21. Academy of Sciences, Ukrainian SSR, Report No. FTD-TT-61-68, Available OTS, "Effect of Initial Disturbances on the Development of Turbulent-Stream Conditions in the Movement of Air Through Tubes," Shvets', I. T., Dyban, E. P., et al., 1960.

An experimental study of the effect of entrance conditions on hydraulic resistance and heat transfer in a tube is described.

22. American Society of Mechanical Engineering, "Symposium on Fully Separated Flows," Edited by Arthur G. Hansen, 136 pp, ASME, New York, 1964.

This volume of 17 papers and abstracts focuses on fluid-control devices. However, papers are included on flow development in diffusers and flow around cylinders and curves.

23. Brown Engineering Company, Inc., Technical Note R-77, "A Review of Flow in Curved Ducts and a Proposed Cross-Sectional Shape to Reduce Environmental Effects Encountered with High-Enthalpy Fluids," Gwinn, G. R., 33 pp, December 1963.

A brief review of the characteristics of fluid flow in ducts is presented.

24. Brown, O. G., and Marris, A. W., "Turbulent Flow of Water in Plane-Curved Channels of Finite Depth," ASME Transactions, Journal of Basic Engineering, Vol. 85, Ser. D, No. 3, pp 377-391, September 1963.

An experimental study of turbulent flow in a plane-curved channel by means of measured distributions of mean-peripheral velocity, and pressure and flow-visualization methods using dye is described.

25. Campbell, W. D., Slattery, J. C., "Flow in the Entrance of a Tube," ASME Transaction, Journal of Basic Engineering, Vol. 85, Ser. D., No. 1, pp 41-46, March 1963.

Analytical development of an expression describing the velocities and pressure within tube entrances for steady-state laminar flow of incompressible Newtonian fluids.

26. D'Souza, A. F., and Oldenburger, R., "Dynamic Response of Curved Fluid Lines," ASME Paper 64-WA/FE-, to be presented at ASME Winter Annual Meeting, New York, December 3, 1964.

27. Fox, R. W., and Kline, S. J., "Flow Regimes in Curved Subsonic Diffusers," ASME Transactions, Journal of Basic Engineering, Vol. 84, pp 303-316, 1962.

The flow in two-dimensional diffusion as a function of included angle and ratio of wall length to throat width is investigated. Below a rather small angle, which decreases as the length of wall increases, the flow spreads out between the walls. Above this

critical angle the pattern is unstable, and then as the angle increases, the flow breaks away from one wall. At a still higher angle, jet action occurs; this transition shows considerable hysteresis.

28. General Electric Company, Aircraft Nuclear Propulsion Department, Report No. DC-57-10-56, Available OTS, "Investigation of the Aerodynamic Performance of a Supentine Duct," Weeden, C. R., Cristenberry, R. E., et al., October 4, 1957.

An experimental study of the flow in a wavy or "serpentine" duct is reported. This study included static-pressure loss, relationship between friction factor and Reynolds number, and total-pressure loss.

29. Izvestiia Akad, Nauk SSSR, Otdelenie Tekhnicheskikh Naui, Report No. AEC-TR-5214, Available OTS, "Turbulent Flow in Circular Tubes," Smirnow, V. I., and Nevzglyadov, V. G., 34 pp, 1945.

A theoretical investigation of the steady flow of an incompressible viscous fluid is described. Derived equations are compared with experimental data and found to be in close agreement.

30. Marris, A. W., "The Generation of Secondary Vorticity in an Incompressible Fluid," Journal of Applied Mechanics, ASME, Transactions, Vol. 30, Ser. E, No. 4, pp 525-531, December 1963.

Analytic development of an expression describing secondary vortices in curved channels.

31. Marris, A. W., "Radial Distributions of Temporal-Mean Peripheral Velocity and Pressure for Fully Developed Turbulent Flow in Curved Channels," ASME Transactions, Journal of Basic Engineering, Vol. 82, Ser. D, No. 3, pp 528-538, September 1960.

Experimental results for the radial distributions of pressure and peripheral velocity for the turbulent flow of water in two closed-curved channels of rectangular cross section and large depth-to-width ratio.

32. Massachusetts Institute of Technology, Department of Mechanical Engineering, Report No. OOR-1935:2, Available OTS, "Fully Developed Turbulent Flow in Straight Rectangular Ducts - Secondary Flow, Its Cause and Effect on the Primary Flow (Thesis)," Hoagland, Lawrence C., 156 pp, September 1960.

Experimental determination of primary and secondary velocity distributions in ducts with aspect ratios of 1:1, 2:1, and 3:1. The effect of secondary flow on primary-flow distribution is discussed. Velocity distributions are given.

33. Olson, R. M., and Sparrow, E. M., "Measurements of Turbulent Flow Development in Tubes and Annuli with Square or Rounded Entrances," American Institute of Chemical Engineering Journal, Vol. 9 (6), pp 766-770, November 1963.

Measurements are reported on the flow development in tubes and annuli with square or rounded entrances.

34. Ringleb, F. O., "Two-Dimensional Flow with Standing Vortexes in Ducts and Diffusers," ASME Transactions, Vol. 82, Ser. D, No. 4, pp 921-928, December 1960.

Potential-flow theory has been used to derive the condition for a pair of standing vortexes in a two-dimensional duct. Properly shaped cups in duct walls can be used as a basis for holding vortexes to form a diffuser section.

SEE ALSO REFERENCE NUMBER 10, 11, 13, 18, 35, 36, 60.

MIXING

35. Aeronautical Research Council, Fluid Motion Subcommittee, Report No. A.R.C. 22,008, "Turbulent Wall Jets with and without an External Stream," Bradshaw, B. A., and Gee, M. T., AD 245 766, 66 pp, 14 June 1960.

The results are presented of experiments on wall jets in still air on flat and curved surfaces and beneath an external stream both with and without pressure gradients and initial-boundary layers.

36. Army Missile Command, Harry Diamond Laboratories, Report No. TR-1087, "Fluid Amplification, 5. Jet-Attachment Distance as a Function of Adjacent Wall Offset and Angle," Levin, S. G., and Manion, F. M., AD 297 895, 45 pp, 31 December 1962.

Attachment of submerged, incompressible, two-dimensional turbulent jet to an adjacent straight wall (Coanda effect) is analyzed. Parametric equations are developed that predict the point at which the jet attaches as a function of wall angle and offset distance.

37. Becker, H. A., Hottel, H. C., and William, G. C., "Mixing and Flow in Ducted Turbulent Jets," Ninth Symposium on Combustion, 7, 1963.

The flow occurring when a jet is discharged axially downstream along a duct is examined by using an aerosol fog in the jet. Particular emphasis is placed on the region of operating conditions wherein recirculation occurs. The results are in general agreement with the Croya-Curtet theory.

38. Burn, E. A., Castel, L., Faulman, D., "Sue un Curieux Cos D'alternance de Tourbillons," Tec. Note N.T. 58, Pub. Sci. et Tech., du Min. de L'air, Paris, 1956.

The conditions governing the frequency of oscillation of a jet discharging into a wide but thin duct with a dead end in line with the jet and an exit surrounding the inlet jet are studied. The alternate build-up and discharge of vortexes is covered in detail by use of sketches. In spite of the considerable amount of data, the equation suggested for predicting frequency does not seem to be sufficiently general.

39. University of California, Lawrence Radiation Lab, Report No. UCRL-10556, Available OTS, "Turbulent Exchange of Momentum, Mass, and Heat Between Fluid Streams and Pipe Wall," Wasan, D. T., and Wilke, C. R., March 1, 1963.

Correlation describing mass and heat transfer to a fluid in fully developed turbulent flow in a pipe based on theoretical continuous eddy-viscosity distribution from the wall to the center of the pipe. Transfer rates calculated using the correlation are in excellent agreement with experimental data.

40. Chigier, N. A., and Beer, J. M., "Velocity and Static-Pressure Distributions in Swirling Air Jets Issuing from Annular and Divergent Nozzles," ASME Paper No. 64-FE-12, May 1964.

The effect on the exit flow from a duct of four different ratios of axial flux of angular momentum to axial flux of linear momentum was determined. The principal feature of the flow patterns was the ring vortex set up just downstream of the exit by the reverse flow along the axis. Adding a divergent section increased the size and strength of the vortex.

41. Curtet, R., "Confined Jets and Recirculation Phenomena With Cold Air," Combustion and Flame, Vol. 2, page 383, 1958.

A theoretical treatment of the flow and recirculation patterns in both two-divergent and axially-symmetric ducts with a superimposed axially-directed jet is followed by a comparison with experimental results. In the two-divergent case, the oscillating flow was observed at low ratios of total flow to nozzle flow; and empirical correlation for predicting the frequency is presented. In the axially-symmetric case, attention is given mainly to means of predicting the amount of recirculation and size of the recirculation zone.

42. Curtet, R., and Ricou, F. P., "On the Tendency to Self-Preservation in Axisymmetric-Ducted Jets," ASME Paper No. 64-FE-20, May 1964.

The change in velocity profile and the level of turbulence are examined theoretically and experimentally for a jet discharging axially downstream in a duct. Similarity theory was applied to that part of the jet flow which excluded the main-duct velocity. This approach was moderately successful.

43. General Dynamics/Convair, Report No. GD/C 62-354A, "Research on Coaxial-Jet Mixing," Cruse, R. E., and Tontini, R., ONR Contract No. 2854(00), 64 pp, AD 298 612, November 1962.

This is a program directed toward development of design parameters for subsonic jet pumps. A mixing tube was developed to give a constant static pressure along its length at the design ratio of mixing-tube velocity to drawing-jet velocity.

44. Keffer, J. F., and Baines, W. D., "The Round Turbulent Jet in a Cross-Wind," Journal of Fluid Mechanics, Vol. 15, page 481, 1963.

45. Levenspiel, O., "Longitudinal Mixing of Fluids Flowing in Circular Pipes," Industrial and Engineering Chemistry, Vol. 50, (3), pp 343-346, March 1958.

Previous experimental work on longitudinal mixing is summarized and compared with theoretical predictions.

46. Rummel, K., Arch. Eisenhuttenq Vol. 10, p 505, April 1937; Vol. 10, p 571, June 1937; Vol. 11, p 19, July 1937; Vol. 11, p 67, August 1937; Vol. 11, p 113, September 1937; Vol. 11, p 163 October 1937; Vol. 11, p 215, November 1937.

In this classic series of papers, Rummel studied the mixing of impinging air jets by mixing ½-percent H_2 in one air jet. The composite profile was then determined.

47. Stanford University, Department of Mechanical Engineering, Technical Report No. 1, "The Plane Turbulent Wall Jet Part 1. Jet Development and Friction Factor," Myers, G.E., Schauer, J. J., and Eustis, R.H. Prepared under NSF Grant G9705, 33 pp, AD 260 778, June 1, 1961.

This report describes an investigation of the jet development, the velocity profiles, and the wall-shearing stress in a two-dimensional, incompressible, turbulent wall jet. Experimental data concerning velocity profiles decay of the maximum velocity, and the jet growth are presented.

48. Trichacek, L. J., Barkelew, C. H., and Baron, T., "Axial Mixing in Pipes," American Institute of Chemical Engineering Journal, Vol. 3, (4), pp 439-442, December 1957.

The problem of axial mixing in straight pipes is analyzed. The effects of both the Schmidt and Reynolds numbers are included throughout the turbulent-flow range.

FLOW MEASUREMENT AND VISUALIZATION INCLUDING FLOW MODELING

49. American Society of Mechanical Engineers, "Flow Measurement by Means of Thin-Plate Orifices, Flow Nozzles, and Venturi Tubes," Chapter 4 of Part 5 - Measurement of Quantity of Materials, Supplement on Instruments and Apparatus, 92 pp, February 1959.

The ASME Standards on flow-measuring devices are presented along with other information useful in the construction and use of these instruments.

50. American Society of Mechanical Engineers, "Fluid Meters, Their Theory and Application," Report of ASME Research Committee on Fluid Meters, 5th Edition, 203 pp, ASME, New York, 1959.

Information on the construction of fluid meters, the recommended techniques governing tests, and the necessary equations for computing rates of flow is presented. An outline of the major advantages and disadvantages of the various types of primary elements is also given.

51. American Society of Mechanical Engineers, "Flowmeter Computation Handbook," Prepared by the ASME Research Committee on Fluid Meters, 169 pp, New York, 1961.

This book has reduced the theoretical and empirical constants given in the Fluid Meter Report to practice, to make available a uniform method of computing flow rates or sizing primary elements.

52. American Society of Mechanical Engineers, Symposium on Flow Visualization-, Presentation Summaries, ASME Annual Meeting, November 1960.

Summaries, varying from rather short to rather extensive, are given for 16 papers on various methods of flow visualization in liquids and gases. Several of the summaries are accompained by photographs showing the type of data resulting from the particular technique.

53. American Society of Mechanical Engineers, "Symposium on Measurement in Unsteady Flow," Presented at Hydraulic Division Conference, Worcester, Mass., May 21-23, 1962, 114 pp, ASME, New York, 1962.

This symposium presents the state of existing knowledge and some recent developments in the techniques of unsteady-flow measurements. Included are a pressure-transducer survey and fundamentals of hot-wire anemometry, for example.

54. Battelle Memorial Institute, AEC Report No. BMI-1337 (CONFIDENTIAL), "An Analysis of Reactor-Flow-Model Studies," Ungar, E. W., and Putnam, A. A., Prepared for Navy Department Bureau of Ships, Contract No. NObs-65057, 102 pp, April 23, 1959.

Various reactor-flow-study programs are discussed and techniques and results compared.

55. Battelle Memorial Institute, AEC Report No. BMI-1397, "Model Studies of Flow and Mixing in the Partially Enriched Gas-Cooled Reactor," Flanigan, L. J., Whitacre, G. R., and Hazard, H. R., 34 pp, November 30, 1959.

Experimental data on core-flow distributions, plenum-flow patterns and mixing, pressure losses, and annular thermal-shield flow are obtained for air in a quarter-scale model. These results are then converted to values applicable to helium flow in the prototype.

56. Battelle Memorial Institute, AEC Report No. BMI-1582, "Studies of Flow and Mixing in a 0.4-Scale Model of the PWR Core 2 Reactor," Flanigan, L. J., Whitacre, G. R., and Hazard, H. R., 50 pp, June 26, 1962.

Modeling techniques, using air as the working fluid, are described in which design data applicable to water flow in PWR Core 2 are obtained. Data include core-flow distributions, pressure drops, and mixing for three model configurations. Additional data are included in a series of earlier reports: BMI-1141, BMI-1172, BMI-1198, BMI-1258, and BMI-1342.

57. Boucher, D. G., and Alves, G. E., "Dimensionless Numbers," Chemical Eigineering Progress, Vol. 55, (9), pp 55-65, September 1959; Vol. 59, (8), pp 75-83, August 1963.

A very complete list of dimensionless numbers is presented in two parts. In addition to serving as a ready reference for the meaning of such numbers, this tabulation can assist in the proper labeling of coefficients in non-dimensionalized differential equations and facilitate proper selection of groupings that arise in model and scale-up studies.

58. University of California, Lawrence Radiation Laboratory, Report No. UCRL-6400, Available OTS, "Theories of Liquid Viscosity," Brush, Stephen G., June 30, 1961.

Review and analysis of current theories on viscosity. Extensive bibliography and list of references.

59. Chesters, J. H., "The Aerodynamic Approach to Furnace Design," Journal of Engineering for Power, Vol. 81, p 361, 1959.

This paper gives a broad-based treatment of the use of flow models and flow tracers in determining the performance characteristics of various types of furnaces obtained in diagnosing and correcting design deficiencies is emphasized.

60. Davis, R. E., "The Visual Examination of Gas Flow Round Pipe Bends Using a New Aerosol Technique," International Journal of Air and Water Pollution, Vol. 8, p 177, 1964.

A stream in which a contained aerosol has partially settled out is sent through a bend to the cross section of interest, where it is sucked through a filter. The impaction pattern reveals the distortion of the flow by the bend. Several patterns showing the effect of Reynolds number,

distance around the bend, relative radius of the bend, and obstacles in the bend are presented.

61. Kline, S. J., and Runstadler, P. W., "Some Preliminary Results of Visual Studies of the Flow Model of the Wall Layers of the Turbulent-Boundary Layer," Journal of Applied Mechanics, Vol. 26, Ser. E, No. 2, pp 166-170, June 1959.

Qualitative experimental study involving positive, zero, and negative pressure gradients, readjusting zones, and later stages of transition.

62. Los Alamos Scientific Laboratory of the University of California, Report No. LA-2806, Available OTS, "Theory of the Correspondence Between Fluid Dynamics and Particle-and-Force Models," Harlow, Francis H., 48 pp, January 17, 1963.

Analysis of the use of a particle-and-force computing method as a statistical representation of the true dynamics of a fluid.

63. Massachusetts Institute of Technology, Gas Turbine Laboratory, Aerodynamic Measurements, Edited by R. C. Dean, Jr., 272 pp, The MIT Press, Cambridge Press, Cambridge, Mass., 1953.

A comprehensive survey of techniques and instruments used in all areas of aerodynamic measurement.

SEE ALSO REFERENCE NUMBERS 24, 94, 95.

CAVITATION AND TRANSIENTS

64. Aeroprojects, Inc., AEC Report NYO-10010, "Ultrasonic Instrumentation in Nuclear Application. I. Detection of Incipient Boiling and Cavitation," De Prisco, C. F., Kartluke, H., Marapis, N., and Tarpley, W. G., 20 pp, March 1962.

    A means for detecting cavitation through noise response is described. The probe-coupler systems used in the work were shown to be capable of detecting the cavitation threshold at a number of different levels of temperature and pressure in water with good sensitivity.

65. American Society of Mechanical Engineers, "Symposium on Cavitation Research Facilities and Techniques," Edited by J. M. Holl and G. M. Wood, 196 pp, ASME New York, 1964.

    This report contains the papers presented at a symposium held at the Fluid Engineering Division Conference in Philadelphia, May 18-20, 1964. Many of the major water-tunnel facilities are described, and five major research areas are included: cavitation damage, cavity flows, cavitation inception and desinence, cavitation noise, and cavitation in turbomachinery.

66. Clark, J., "A New Method for Detecting Cavitation and Turbulence in Cryogenic Fluids," Advances in Cyrogenic Engineering, Vol. 4, K. D. Timmerhaus, Editor, Plenum Press, Inc., New York, 1960, pp 203-217.

    The phenomenon in which an omnidirectional magnetic field is generated adjacent to a vapor bubble in a liquid has been applied to the detection of cavitation in various liquid flows.

67. Hammitt, F. G., "Observation of Cavitation Scale and Thermodynamic Effects in Stationary and Rotating Components," ASME Transactions, Journal of Basic Engineering, Vol. 85, Ser. D, No. 1, pp 1-16, March 1963.

    This paper presents experimental measurements for a venturi test section and a centrifugal pump. Theoretical expectations and comparisons with previous investigators' data are discussed.

68. Harden, D. B., and Walker, R, J., "Heat-Driven Pressure and Flow Transients in a Closed Circulating System," ASME Paper 64-WA/HT-, to be presented at ASME Winter Annual Meeting, New York, December 3, 1964.

69. Holl, J. W., "An Effect of Air Content on the Occurrence of Cavitation," ASME Transactions, Journal of Basic Engineering, Vol. 82, Ser. D, No. 4, pp 941-946, December 1960.

The simultaneous occurrence of vaporous and gaseous cavitation on hydrofoils is considered. The experimental results show that gaseous cavitation occurs at much higher ambient pressure than for vaporous cavitation.

70. Hord, J., Jacobs, R. B., Robinson, C. C., and Sparks, L. L., "Nucleation Characteristics of Static Liquid Nitrogen and Liquid Hydrogen," ASME Transactions, Journal of Engineering for Power, Vol. 86, Ser. A, No. 4, pp 485-494, October 1964.

Characteristics which control the existence of metastable (superheated) liquid states and the nucleation of the vapor phase are studied. Knowledge of these characteristics aids in the design of cryogenic equipment.

71. Jakobsen, J. K., "On the Machanism of Head Breakdown in Cavitating Inducers," ASME Transactions, Journal of Basic Engineering, Vol. 86, Ser. D, No. 2, pp 291-305, June 1964.

The mechanism of head breakdown in cavitating inducers, as affected by thermodynamic properties of the pump fluid and scale effects, is discussed. The approach taken by other investigators is presented, and the limitations to cavitation scaling are examined in relation to experimental data.

72. Lehman, A. F., and Young, J. O., "Experimental Investigations of Incipient and Desinent Cavitation," ASME Transactions, Journal of Basic Engineering, Vol. 86, Ser. D, No. 2, pp 275-284, June 1964.

Experiments with water in a high-speed recirculating water tunnel to measure pressure at which incipient and desinent cavitation occurred. Both smooth and abrupt contour changes were tested with significant differences found.

73. NASA Lewis Research Center, TN-D-1459, "Effects of Air Content and Water Purity on Liquid Tension at Incipient Cavitation in Venturi Flow," Ruggeri, R. S., and Gelder, T. F., March 1963.

In the work reported here, no effect of air content and water purity on liquid tension was found for water in venturi flow over the range studied. Increasing air content did result in other problems, however.

74. NASA Lewis Research Center, TN-D-2088, "Cavitation of Nitrogen in a Tunnel Venturi," Ruggeri, R. S., and Gelder, T. F., 33 pp, February 1964.

Cavitation of liquid nitrogen was induced on the walls of a tunnel venturi. Compared with previous cavitation tests of room-temperature water in the same venturi, nitrogen sustained nearly twice the effective tension and exhibited temperature depression at least one order of magnitude greater.

75. Numachi, F., Kobayashi, R., and Kamiyama, S., "Effect of Cavitation on the Accuracy of Herschel-Type Venturi Tubes," ASME Transactions, Journal of Basic Engineering, Vol. 84, Ser. D, No. 3, pp 351-362, September 1962.

The effect of cavitation in a Herschel-type venturi tube was determined for a variety of conditions. Additional restrictions on the radii to keep deviations within certain limits are also presented.

76. Office of Naval Research, NOX 61-2-1, "Second Symposium of Naval Hydrodynamics, Hydrodynamics Noise, and Cavity Flow," Edited by R. D. Cooper, 583 pp, AD 250 229, 1958.

This report contains all the papers presented at the symposium. Two areas are stressed: hydrodynamic noise and supercavitating flow. However, much general information on cavitation is also presented.

77. Pennsylvania State University, Ordnance Research Lab, Contract No. NOw 63 0209c, "A Method for the Design of Pumpjets," Henderson, R. E., McMahon, J. F., and Wislicenus, G. F., AD 439 631, 50 pp, 15 May 1964.

For certain applications, the pumpjet can be designed to have better cavitation characteristics than an open propeller. A quasi one-dimensional method of blade design but still meets the stringent requirements regarding cavitation.

78. Princeton University, Plasma Physics Laboratory, AEC Report MATT-142, "Detection and Location of Cavitation," Kittredge, C. P., 39 pp, August 1962.

This report describes the use of an accelerometer to detect and also determine the location of cavitation in a pipeline.

79. Salemann, V., "Cavitation and NPSH Requirements of Various Liquids," ASME Transactions, Journal of Basic Engineering, Vol 81, Ser. D, No. 2, pp 167-180, July 1959.

Test results on the net positive suction-heat (NPSH) requirement for centrifugal pumps handling water up to 420°F, some hydrocarbons, and Freon-11 are presented. The cavitation process is discussed, and methods of prediction for all liquids are proposed.

80. Shulter, N. D., and Mesler, R. B., "A Photographic Study of the Dynamics and Damage Capabilities of Bubbles Collapsing Near Solid Boundaries," ASME Paper 64-WA/FE-13, to be presented at ASME Winter Annual Meeting, New York, December 3, 1964.

81. Spraker, W. A., "The Effects of Fluid Properties on Cavitation in Centrifugal Pumps," ASME Paper 64-WA/FE-, to be presented at ASME Winter Annual Meeting, New York, December 2, 1964.

Results of cavitation tests with a variety of fluids are correlated utilizing a fluid-property parameter. This parameter can then be used to estimate cavitation effect for other fluids, also.

82. Stahl, H., and Stepanoff, A. J., "Thermodynamics Aspects of Cavitation in Centrifugal Pumps," ASME Transactions, Vol. 78, pp 1691-1693, 1956.

The effect of liquid properties on centrifugal pump behavior under cavitation conditions is examined on the basis of a given pump handling various liquids. A criterion in terms of physical properties of the liquid is established that can be used to indicate cavitation effects on pump performance for various liquids.

83. Stepanoff, A. J., "Cavitation in Centrifugal Pumps with Liquids Other Than Water," ASME Transactions, Journal of Engineering for Power, Vol. 83, Ser. A, No. 1, pp 79-90, January 1961.

Conditions leading to cavitation of liquids other than water are examined. The concept of the thermal-cavitation criterion is considered and its utility for determination of NPSH corrections is demonstrated.

84. Stripling, L. B., and Acosta, A. J., "Cavitation in Turbopumps," ASME Transactions, Journal of Basic Engineering, Vol. 84, Ser. D, No. 3, pp 326-350, September 1962.

Cavitation-performance data of several helical inducers for various flow coefficients are correlated with existing theory. A method is developed which employs semiempirical-correlation coefficients to supplement idealized free-streamline solutions.

85. Wood, G. M., Murphy, J. S., and Farquhar, J., "An Experimental Study of Cavitation in a Mixed-Flow Pump Impeller," ASME Transactions, Journal of Basic Engineering, Vol. 82, Ser. D, No. 4, pp 929-940, December 1960.

A mixed-flow impeller design was tested in a closed water loop to study the effects of cavitation on hydraulic performance, and the results are compared with the work of other investigators. Two idealized-flow models for incipient cavitation were derived to illustrate limits of cavitation design.

FLOW OF CRYOGENIC FLUIDS

86. Burke, J. C., Byrnes, W. R., Post, A. H., and Ruccia, F. E., "Pressurized Cooldown of Cryogenic Transfer Lines," Advances in Cryogenic Engineering, Vol. 4, K. D. Timmerhaus, Editor, Plenum Press, Inc., New York, 1960, pp 378-394.

A model is developed to predict the cooldown time of cryogenic systems. Although the model does not consider the dynamics of the system, it has been used with success and is apparently the only published method available.

87. Corruccini, R. J., "Temperature Measurements in Cryogenic Engineering," Advances in Cryogenic Engineering, Vol. 8, K. D. Timmerhaus, Editor, Plenum Press, Inc., New York, 1963, pp 315-333.

A summary of temperature-measurement techniques covering the entire cryogenic range is presented. Calibration methods and temperature scales are also discussed. An extensive bibliography is included.

88. Jacobs, R. B., "How Low Temperatures Encountered Affect Design, Installation, and Operation of Cryogenic Piping Systems," Heating, Piping, and Air Conditioning, Vol. 32 (5), pp 143-156, May 1960.

Fluid-flow considerations, pumps, and instrumentation are stressed in this second of a two-part series on design problems unique to cryogenic piping systems.

89. Jacobs, R. B., "What to Consider When Designing Cryogenic Piping Systems," Heating, Piping, and Air Conditioning, Vol. 32 (2), pp 130-140, February 1960.

A general discussion is presented of some of the design problems unique to cryogenic piping systems.

90. LeValley, W. H., and Sutton, W. K., "Design of Piping for Cryogenic Fluids," Advances in Cryogenic Engineering, Vol. 6, K. D. Timmerhaus, Editor, Plenum Press, Inc., New York, 1961, pp 293-301.

Special problems in the design of piping for cryogenic fluids are considered. An economic study of the use of various vacuum insulations is included. Typical connections, other components, and materials of construction are also discussed.

91. National Bureau of Standards, Cryogenic Engineering Laboratory, Boulder, Colorado, Circular 596, "Single-Phase Transfer of Liquefied Gases," Jacobs, R. B., 42 pp, December 1958.

The problems encountered in the single-phase transfer of liquefied gases are discussed in detail. Although directed toward long-distance transfer in pipe, much of the information applies to liquefied-gas flow in general.

92. National Bureau of Standards, Cryogenic Engineering Laboratory, Boulder, Colorado, Report No. 3569, "Pumping Cryogenic Liquids," Jacobs, R. B., Martin, K. B., Van Wylen, G. J., and Birmingham, B. W.

Some of the special problems encountered in pumping cryogenic liquids are discussed.

93. National Bureau of Standards, Cryogenic Engineering Laboratory, Boulder, Colorado, NBS Technical Note No. 129, "The Thermodynamic Properties of Nitrogen from 64° to 300°K Between 0.1 and 200 Atmospheres," Strobridge, T. R., January 1962.

This report includes P-V-T as well as enthalpy and entropy-property tables for nitrogen in the ranges listed in the title. A temperature-entropy chart is also available separately.

94. Richards, R. J., Jacobs, R. B., and Pestalozzi, W. J., "Measurement of the Flow of Liquefied Gases with Sharp-Edged Orifices," Advances in Cryogenic Engineering, Vol. 4, K. D. Timmerhaus, Editor, Plenum Press, Inc., New York, 1960, pp 272-285.

This report demonstrates that the sharp-edged orifice can be used with liquefied gases. There are certain limitations, however, and these are discussed.

95. Purcell, J. R., Schmidt, A. F., and Jacobs, R. B., "The Venturi Tube as a Liquefied Gas Flow-Measuring Device," Advances in Cryogenic Engineering, Vol. 5, K. D. Timmerhaus, Editor, Plenum Press, Inc., New York, 1960, pp 282-288.

Tests on a venturi tube used for liquid-hydrogen metering are reported. Experimental accuracies are listed and discussed to the extent that they influence the test results. The usefulness as well as the limitations of the venturi as a low-temperature fluid meter are indicated.

96. Scott, R. B., Cryogenic Engineering, D. Van Nostrand Co., Inc., Princeton, New Jersey, 1959.

This book is the standard reference in the field of cryogenic engineering. It consolidates in a single text information from numerous sources and presents it in easily understandable terms.

97. Surdi, V. L., and Romaine, D., "Fundamentals of Low-Temperature Piping Design," Hydrocarbon Processing and Petroleum Refiner, Vol. 43 (6), pp 116-124, June 1964.

A general discussion of low-temperature piping is presented. Particular emphasis is placed on piping materials, gasket materials, and insulation.

SEE ALSO REFERENCE NUMBERS 70, 74, 99.

TWO-PHASE FLOW

98. Argonne National Laboratory, Report No. ANL-6734, "Two-Phase (Gas-Liquid) System: Heat Transfer and Hydraulics. An Annotated Bibliography," Kipple, R. R., and Tung, T. V., 428 pp, July 1963.

A very extensive bibliography is presented covering the areas of heat transfer and hydraulics in gas-liquid systems. Abstracts are given for nearly all references.

99. Hatch, M. R., and Jacobs, R. B., "Prediction of Pressure Drop in Two-Phase Single-Component Fluid Flow," American Institute of Chemical Engineering Journal, Vol. 8 (1), pp 18-25, March 1962.

Data on pressure drop in two-phase single-component fluid flow, both with and without heat transfer, are presented in terms of Lockhart and Martinelli correlation parameters. Data on liquid hydrogen flowing with large heat flux are included. It is concluded that the Martinelli and Nelson correlation and a simple momentum pressure-drop computation can be superposed to predict roughly the total pressure drop in tubes containing steady-state, two-phase, single-component fluid flow with appreciable vaporization.

100. Lockhart, R. W., and Martinelli, R. C., "Proposed Correlation of Data for Isothermal Two-Phase, Two-Component Flow in Pipes," Chemical Engineering Progress, Vol. 45 (1), pp 39-48, January 1949.

This article presents the Martinelli pressure-drop model. Although many other models and improvements have been introduced, this model is still generally accepted as a usable approach with sufficient accuracy.

101. Massachusetts Institute of Technology, Department of Mechanical Engineering, Report No. DSR-8734-1, "An Index to the Two-Phase Gas-Liquid Flow Literature - Part I," Gouse, S. W., Jr., Prepared for Office of Naval Research under Contract Nonr-1841(73), 515 pp, May 1963.

A total of 2000 separate references on certain types of two-phase gas-liquid flow phenomena have been found, verified, listed, and indexed by subject and principal author.

102. Westinghouse, Atomic Power Division, Report No. WAPD-TH-360, "Literature Survey of Two-Phase Fluid Flow," Masnovi, R., 53 pp, May 1957.

The various models for predicting two-phase pressure drops are summarized and compared.

SEE ALSO REFERENCE NUMBER 8.

PERSONAL AUTHOR INDEX

PERSONAL AUTHOR INDEX (Continued)

PERSONAL AUTHOR INDEX (Concluded)

DISTRIBUTION

	Number of Copies
Headquarters Defense Documentation Center for Scientific and Technical Information Cameron Station (Bldg. 5) Alexandria, Virginia 22314	20
U. S. Army Missile Command Distribution List A for Technical Reports (December 1964)	84
RSIC Supplemental Distribution List A	21
Battelle Memorial Institute 505 King Avenue Columbus 1, Ohio	25
National Aeronautics and Space Administration George C. Marshall Space Flight Center Redstone Arsenal, Alabama Attn: MS-T, Mr. Wiggins	5
R-P&VE-PE, Mr. Mann	12
AMSMI-XE, Mr. Lowers	1
-XS, Dr. Carter	1
-R, Mr. McDaniel	1
-RAA	1
-RAP	1
-RBR	50
-RBLD	10

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Redstone Scientific Information Center Directorate of Research and Development U. S. Army Missile Command Redstone Arsenal, Alabama 35809	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE

WATER TUNNEL DESIGN AND RELATED INSTRUMENTATION CONSIDERATIONS AND A SELECTED BIBLIOGRAPHY ON INCOMPRESSIBLE, INTERNAL FLUID FLOW

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

None

5. AUTHOR(S) *(Last name, first name, initial)*

Harp, J. L., Hoehne, V. O., Allen, J. M., and Whitacre, G. R.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1964	53	32

8a. CONTRACT OR GRANT NO. DA-01-021-AMC-203(Z)	9a. ORIGINATOR'S REPORT NUMBER(S) RSIC-328
b. PROJECT NO. c. d.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* AD

10. AVAILABILITY/LIMITATION NOTICES

Qualified requesters may obtain copies of this report from DDC.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	Same as 1

13. ABSTRACT

This report presents the results of a state-of-the-art survey on flow-tunnel design and related instrumentation for tunnels using water or liquid nitrogen as the working fluid. The scope of the survey is purposely narrowed by considerations of the proposed tunnel to be designed and built at the NASA Marshall Space Flight Center. Initial application of the proposed tunnel will include internal-fluid-flow studies of cryogenic fuel-system components or combinations thereof.

Major considerations applicable to the principal components of the proposed tunnel are presented. Some specific recommendations are also presented for consideration by those who will undertake the actual design and operation of the proposed tunnel.

Literature cited is listed at the end of the report for further detailed study. Many of these references are, in themselves, design studies for liquid flow tunnels or flow-tunnel sections.

Also included is a compilation of references on internal fluid flow with a brief description of each. The categories included are pressure drop, flow patterns including curved flows, mixing, flow measurement and visualization including flow modeling, cavitation and transients, flow of cryogenic fluids, and two-phase flow.

DD FORM 1 JAN 64 1473

lca

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Water Tunnel - Design						
Water Tunnel - Instrumentation						
Fluid Flow - Pressure Drop and Mixing						
Fluid Flow - Patterns						
Fluid Flow - Measurement						
Fluid Flow - Cavitation and Transients						